The little observatory in the garden of the Real School at Odder has been altered in the past year, so that the dome which formerly could be opened in six directions can now be turned around.

FIRST AWARD OF THE BRUCE MEDAL.

The award for 1898 of the BRUCE Medal of the Astronomical Society of the Pacific has been made to Professor SIMON NEWCOMB.

SPECTROSCOPIC BINARY STARS.

BY R. G. AITKEN.

The announcement made in Harvard College Observatory *Circular*, No. 21, that *β Lupi* is a spectroscopic binary, calls new attention to one of the most interesting classes of stars known. Binary star systems—that is, systems comprising two suns in orbital motion about a common center of gravity—have been known since the time of HERSCHEL; but their periods of revolution are reckoned in years and even in centuries. The most rapid binary known at the beginning of the present decade needed eleven and a half years to complete a single revolution. Small wonder then, that the startling announcements made by PICKERING and VOGEL that *ζ Ursæ majoris* made a complete revolution in about 105 (later reduced to 52) days, and that *β Persei (Algol)*, *β Aurigæ*, and *α Virginis* had periods of from 2.9 to 4 days, should be received with caution and even with suspicion.

It is true, indeed, that GOODRICKE, who discovered the variable character of the light of *Algol* in 1782, suggested an eclipse of the visible star by a dark body as a plausible explanation of the periodic dimming of its light. But another explanation that found favor was, that *Algol* was a bright star, upon whose photosphere spots analogous to our sun-spots were irregularly distributed, the periodic time of light variation corresponding to the time of axial rotation. At best, GOODRICKE'S hypothesis was classed with other theories, convenient as explanations, but not susceptible of proof. The modern spectroscope, however, by demonstrating that the spectrum of the star was sensibly the

same in quality in all its light phases, disposed of the spot theory; and later, in the skillful hands of VOGEL, proved that GOODRICKE'S hypothesis was substantially correct.

Professor VOGEL photographed the spectrum of *Algol* on many nights, and on each plate photographed also the spectrum of hydrogen. If the star were at rest relatively to the Earth, the hydrogen lines in the star's spectrum should correspond to those in the artificial spectrum. If the star were receding from the Earth, the lines in its spectrum (according to DOPPLER'S principle) should be shifted slightly, with respect to the lines in the hydrogen spectrum, toward the red end, and if approaching the Earth, toward the violet end of the spectrum. Now, VOGEL found that before the obscuration the lines were shifted toward the red end by an amount corresponding to a velocity of recession of about twenty-seven miles a second. After obscuration, the shifting of the lines towards the violet end indicated a somewhat greater velocity of approach. This is just what should happen if a dark body were swinging the bright star around a common center of gravity in an orbit nearly edgewise to the Earth, the whole system meanwhile approaching the Sun.

VOGEL'S results were published in November, 1889. In August of the same year, Professor E. C. PICKERING announced that certain lines in the photographic spectrum of ζ *Ursæ majoris (Mizar)* were found to be double on some plates, single on others. Examination of many plates showed a periodic recurrence of the phenomenon at intervals of about fifty-two days. A little later in the same year, he announced that Miss A. C. MAURY had discovered the same peculiarity in the spectrum of β *Aurigæ*, with the important difference that in the latter star the doubling of the lines occurred at intervals slightly less than two days. The explanation of this phenomenon is, that these stars consist of two components revolving, as in the case of *Algol*, in an orbit turned nearly edgewise to us, each component being bright. When the stars are at right angles to the line of vision (at elongation, that is), one will be moving towards us, the other away from us, and the lines in their spectra are, consequently, shifted in opposite directions. As the stars are so close together that their spectra overlie each other on the plate, the effect is to show the lines in the resulting compound spectrum apparently double.

In April, 1890, VOGEL published his investigations on the spectrum of α *Virginis*. Discordances in the values of the

velocity of the star in the line of sight led to more extended observations, with the result that it was found that the star is moving in a nearly circular orbit, with a period of about four days. As the lines in the spectrum show no evidence of doubling, the companion must be relatively a dark star, as in the case of *Algol*. But as the bright star suffers no diminution in its light, the orbit must be sufficiently inclined to the line of sight to prevent eclipses.

These stars, then, are typical of the three varieties of binary systems whose existence has been demonstrated by the spectroscope, viz. (1) a bright star with a relatively dark companion, the plane of the orbit passing so nearly through the Sun that the brighter star suffers periodic partial or total eclipse; (2) a bright star with a relatively dark companion, the plane of the orbit being so inclined to the line of vision that eclipses are impossible; (3) a system of two bright stars. It is probable that stars of the η *Aquilæ* type—to which attention is called in a note elsewhere in this number — should be included in the second class. Perhaps, too, that puzzling variable, β *Lyræ*, — a variable *sui generis*, one writer calls it—should be included, as PICKERING (H. C. O. Circular 7) classes it with the *Algol*-type variables. Since this observer's discovery of the composite nature of its spectrum, β *Lyræ* has been carefully studied by many observers, and important papers on its photographic spectrum have been published by BELOPOLSKY, VOGEL, SIDGREAVES, LOCKYER, and others. To indicate, even in the briefest manner, the complex nature of the observed phenomena and the various hypotheses that have been framed to account for them, would require a separate article. As it is the purpose of the present paper merely to give some account of our knowledge of the three varieties of binaries above enumerated, it must suffice here to say of β *Lyræ* that, while it is probably binary, no hypothesis has yet been framed that explains completely all the observed changes in light and spectrum.

When VOGEL made public his researches on β *Persei*, ten *Algol*-type variable stars were known. Since then, their number has been increased to fifteen, possibly sixteen. They are here given, together with their discoverers, dates of discovery, approximate periods, range of magnitude, and duration of change. The data are nearly all taken from CHANDLER'S "Third Catalogue of Variable Stars."

NAME.	DISCOVERER.		PERIOD.	MAGNITUDE AND DURATION OF CHANGE.
β Persei (Algol) .	Goodricke,*	1782	$2^d\ 20^h\ 48^m\ 55^s$	2.3 to 3.5 in 10^h
S Cancri	Hind,	1848	9 11 37 45	8.2 to 9.8 in 21½
λ Tauri	Baxendall,	1848	3 22 52 2	3.4 to 4.2 in 10
δ Libræ	Schmidt,	1859	2 7 51 23	5.0 to 6.2 in 12
U Coronæ	Winnecke,	1869	3 10 51 12	7.5 to 8.9 in 10 nearly
U Cephei	Ceraski,	1880	2 11 49 38	7.1 to 9.2 in 10
U Ophinchi . . .	Sawyer,	1881	0 20 7 43	6.0 to 6.7 in 5
Y Cygni	Chandler,	1886	1 11 57 28	7.1 to 7.9 in about 8
R Canis Majoris.	Sawyer,	1887	1 3 15 46	5.9 to 6.7 in 5
S Antliæ † . . .	Paul,	1888	0 7 46 48	6.7 to 7.3 in about 3½
Z Herculis . . .	Müller & Kempf,	1891	3 23 49.54	7.1 to 8.0
R Aræ	Roberts,	1891	4 10 12.7	6.9 to 8.0 in 10.3
RS Sagittarii . .	Gould,	1874	2 9 58.6	6.4 to 7.5
S Velorum . . .	Woods,	1894	5 22 24.35	7.8 to 9.3 in 15.2
Y Bootis (?) ‡ . .	Parkhurst,	1894	2.6	8.0 to 8.6
W Delphini . . .	Miss Wells,	1895	4 19 21.2	9.5 to $<$ 12 in 3 ±

The eclipse hypothesis was naturally applied to these *Algol*-type stars, but not with immediate and complete success. In the case of *Algol* itself a difficulty was encountered, in that the period was known to be about six seconds shorter than at the time of GOODRICKE'S discovery, while in 1798, and again in 1830, it was slightly longer. The irregularities in the periods of other stars, as, for instance, *S Cancri* and *λ Tauri*, were even more marked; in fact, it is even now impossible to determine the law governing the inequalities of the last-named star.

Dr. CHANDLER (A. J. VII) had investigated the irregularities in *Algol's* period fully; and in 1892 he followed this investigation with the demonstration of a proposition that may be put most briefly in his own words:—

"*Algol*, together with the close companion — whose revolution in $2^d\ 20^h.8$ produces by eclipse the observed fluctuations in light, according to the well-known hypothesis of GOODRICKE, confirmed by the elegant investigation of VOGEL,— is subject to still another orbital motion of a quite different kind. Both have a common revolution about a third body, a large, distant, and dark companion, or primary, in a period of about 130 years.

* Suspected by MONTANARI, 1669.

† Questioned by PICKERING, H. C. O. Circ. 7.

‡ PARKHURST'S idea that this star is of the *Algol*-type has not yet been confirmed. *X Carinæ* is also suspected to belong to this class, but ROBERTS' announcement still awaits confirmation.

The size of this orbit around the common center of gravity is about equal to that of *Uranus* around the Sun. The plane of the orbit is inclined about twenty degrees to our line of vision. *Algol* transited the plane, passing through the center of gravity perpendicular to this line of vision, in 1804 going outwards, and in 1869 coming inwards. Calling the first point the ascending node, the position-angle, reckoned in the ordinary way, is about sixty-five degrees. The orbit is sensibly circular, or of very moderate eccentricity. The longest diameter of the projected ellipse, measured on the face of the sky, is about $2''.7$."

It would take us too far to enter into the proofs of this proposition. It must be sufficient to say that Dr. CHANDLER made out a very strong case, and that subsequent observations and investigations seem to substantiate his argument. CHANDLER further pointed out the fact that analogous irregularities existed in the periods of six, or, perhaps, seven others of the ten stars of this type then known, while two were of too recent discovery to make possible any assertion about the constancy of their periods. "The principle of attributing like effects to like causes allows us to assume, with high probability, that . . . all the stars of this class have similar motions, namely, one around a near companion, the other a common motion of these two bodies around a distant one."

In this connection it is of historical interest to note that Professor WM. FERREL, in 1855, suggested,* as an explanation of the retardation and subsequent acceleration of its period, that *Algol* and its hypothetical close companion revolved about a distant dark companion in a period of perhaps several centuries.

In speaking of *Algol's* close companion, we have called it "*relatively* dark." VOGEL showed that if its light were one eightieth part as intense as that of its primary, a secondary minimum would be produced, caused by the brighter star occulting its faint companion. In at least three of the *Algol*-type stars, viz. *RS Sagittarii*, *Y Cygni*, and *Z Herculis*, this phenomenon has been observed.

According to ROBERTS, the first-named star usually has a magnitude of 6.60; at the chief minimum this becomes 7.59, and at the secondary minimum 6.89. This he accounts for by assuming that one star of the system is nearly twice as bright as

* *Nashville Journal of Medicine and Surgery*, April, 1855. Reprinted in *Astronomy and Astro-Physics*, Vol. XII, p. 429.

the other; that the orbit is eccentric, the line of apsides nearly coinciding with the line of sight; and that the fainter star is almost directly between us and its primary (thus causing the chief minimum) when the stars are at their greatest distance apart.

The secondary minimum in *Y Cygni* differs so little in point of magnitude from the principal one that it is only recognized by the fact that the minima, instead of following each other at uniform intervals, occur at intervals of thirty-two hours and forty hours alternately. Hence, for this star the terms *even* and *odd* minima are used. DUNÉR's explanation of these facts is, that the star consists of two equally large and bright components, revolving about their common center of gravity in an elliptic orbit in a period of nearly three days, the perihelion passages occurring between the even and the odd epochs. The eccentricity of the orbit need only be 0.1 to explain fully all the observations. Observation seems to show that the intervals between even and odd minima are not constant; and this DUNÉR would explain by assuming a third invisible perturbing body, which causes a motion of the line of apsides such as is found in the planets and satellites of the solar system.

Z Herculis differs from *Y Cygni* in that the minima, which occur at intervals of forty-seven and forty-nine hours, respectively, are alternately faint and very bright.

To suit these intervals and magnitudes, DUNÉR finds that we must assume that *Z Herculis* consists of two stars of equal size, one of which is twice as bright as the other. The semimajor axis of the elliptic orbit of the stars is six times their diameter (assuming that one star remains fixed in the focus of the ellipse). The plane of the orbit passes through the Sun, the eccentricity is about 0.25, and the line of apsides is inclined at an angle of four degrees to the line of sight.

While there are still many difficult and interesting problems to solve in connection with the *Algol*-type stars, it is now certain that the solutions will be sought—and probably found—in extensions of the theory of orbital motion; and enough has been said here to indicate the lines along which the investigations are proceeding.

One further characteristic may be mentioned that is common to all these stars, namely, their small mean density. Several investigators have found that the mean density of *Algol* is not

more than one fourth that of water, while other stars of the type are even more tenuous. If these results are correct, the *Algol*-type stars must be completely gaseous.

Turning now to the binary stars which have been revealed by the doubling of the lines in their spectra, we find that, so far, only five have become known to us.

NAME.	DISCOVERER.		PERIOD.
ζ *Ursæ majoris*,	Pickering,	1889	52 days.
β *Aurigæ*,	Miss Maury,	1889	$3^d\ 23^h\ 36.7^m$
μ' *Scorpii*,	Bailey,	1896	1 10 42.5
A. G. C. 10534,	Pickering,	1896	3 2 46
β *Lupi*,	Mrs. Fleming,	1897	Undetermined.

As already stated, ζ *Ursæ majoris* was the first star of this type to reveal its binary character by the periodic doubling of its lines. But it is, nevertheless, the one whose period we are least certain of — with the exception of β *Lupi*, just discovered. As the lines are clearly double about every fifty-two days, the period was at first announced as 104 or 105 days. Later evidence, however, indicates that half this time is the true period, the orbit of the second star about its primary being probably an ellipse of considerable eccentricity, with the major axis nearly perpendicular to the line of sight. In this case the lines would be seen double once in each revolution — at the time of periastron passage,— but would only become broader and blurred at the time of apastron. This theory would seem to fit the observations fairly; but there appear to be irregularities in the period, which may perhaps indicate the presence of a third body. The maximum relative velocity of the two components is found to be about 100 miles per second.

The second star in this list, β *Aurigæ*, is much more rapid and decided in its changes. So rapid, in fact, are the changes in the spectrum, that they are sometimes perceptible, according to PICKERING, in successive photographs, and in the course of an evening are very marked. The distance between the lines when at their greatest separation is so great that measures are easy and accurate. There is a very slight difference in the intensity of the lines, and the fainter line is alternately more and less refrangible than the brighter one. As the measures of the amount of separation in the two positions indicate nearly the same velocity,— about 150 miles per second—it is probable that

the orbit is nearly circular. As the period is four days, it follows, assuming the plane of the orbit to be parallel to the line of sight, that the distance between the stars is about 8,000,000 miles, and the combined mass 2.3 times that of our Sun. If the orbit is inclined to the line of sight, as is probable, these values must be increased by an amount depending on the inclination. PRITCHARD has found the value of the parallax of β *Aurigæ* to be 0″.062; hence the greatest angular separation of the components is less than 0″.01. The most powerful existing telescope, therefore, can never make the components visible to us.

μ' *Scorpii* and *A. G. C.* 10534 resemble β *Aurigæ*, in that their periods of revolution are short and the doubling of the lines very marked. In fact, in these respects they surpass the latter star, as the recent measures by Mrs. FLEMING show that the relative velocities of the components are about 286 and 379 miles per second, respectively. In each of these stars one component is noticeably fainter than the other. The relative intensity of the lines in μ' *Scorpii* seems to change, indicating a possible light variation in one of the components; but this needs further investigation.

If we except the short period variable stars, like η *Aquilæ* and δ *Cephei*, which are almost certainly binary systems, but which require additional hypotheses to account for their variability, we have two stars left which call for brief notice, viz. α *Virginis* (*Spica*) and α' *Geminorum*, the principal component of the well-known double star *Castor*. As has been said above, the former was discovered by VOGEL, in 1890, by the shifting of the hydrogen lines in its spectrum alternately toward the red and violet end, with respect to the lines in an artificially produced spectrum of hydrogen. It was thus found that, while the system is approaching the Sun at the rate of nine miles per second, the two components are in orbital motion, with a velocity of about fifty-seven miles per second, completing one revolution in 4.0134 days. In the same way BELOPOLSKY found, in 1896, that the components of α' *Geminorum* complete a revolution about their common center of gravity in 2.91 days.

That the number of known spectroscopic binary stars will be largely increased by future discoveries, is certain, and it is entirely possible that the study of their phenomena, as shown in light variations and changes in spectrum, may yet reveal to us systems more complex than even our own solar system.

The mathematical formulæ, by means of which the elements of a binary star orbit may be computed from measures of the relative velocities of the components in the line of sight, have been fully developed by RAMBAUT,* WILSING,† and LEHMANN-FILHÉS,‡ but the discussion of their methods and results is beyond the province of this article.

LICK OBSERVATORY, University of California,
January 26, 1898.

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* *Mon. Not. R. A. S.*, March, 1891.
† *A. N.*, 3198.
‡ *A. N.*, 3242.